

# **CARIBU Electron Beam Ion Source (EBIS) Charge Breeder Electron Beam Stability Modeling**

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## **Abstract**

Models have been made to ensure that the electron beam in ATLAS's (Argonne Tandem Linear Accelerator System's) EBIS (Electron Beam Ion Source) charge breeder remains stable and well defined within the trap region. These models have focused on two aspects of possible beam deviation; external magnetic field uniformity and understanding the effect of drift tube misalignments. Additionally, the force exerted on the vacuum pump shielding has been found. The magnetic field uniformity has been investigated through identifying the effect that the magnetic field from the turbo pump shields has on the beam. Helmholtz coils have been designed to compensate for the effects. Preliminary results of the effect of angular drift tube misalignments on the beam emittance are presented.

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# 1. Introduction

Argonne National Laboratory's ATLAS (Argonne Tandem Linear Accelerator System) has recently commissioned the CARIBU<sup>[1]</sup> (CALifornium Rare Isotope Breeder Upgrade). This new isotope source has expanded the species capabilities to include many new neutron rich species.

Many low-energy nuclear experiments require highly charged ions. Several current accelerators and almost all planned rare isotope facilities offer the ability to produce beam using a charge state breeder (charge breeding). One such facility is Argonne's ATLAS. This approach is also utilized at CERN's ISOLDE, TRIUMF's ISAC and will be available at NSCL's re-accelerator project, GANIL's SPIRAL2 and MSU's FRIB<sup>[2]</sup>.

There are two primary ion sources used for charge breeding; an Electron Beam Ion Source (EBIS) and an Electron Cyclotron Resonance Ion Source (ECRIS)<sup>[2]</sup>. EBIS systems have demonstrated efficiencies which are 3-4 time higher depending on the ion species, shorter breeding times, better beam emittances and less superposition of impurities in the beam as compared to ECRIS<sup>[2]</sup>. These qualities are especially important for the radioactive ion beams produced by CARIBU since its beams have relatively low intensities; less than  $10^7$  ions per second<sup>[2]</sup>. Currently an ECRIS breeds beams for CARIBU, but an EBIS is being commissioned to replace the ECRIS and improve the beam quality. A basic schematic of the EBIS system is shown in figure 1.

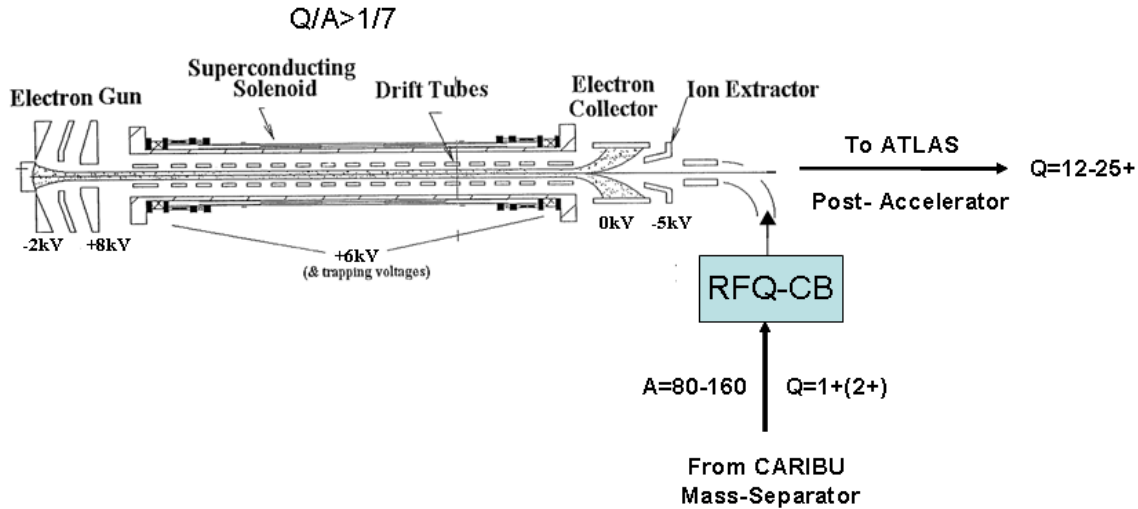


Fig 1 : Design of ATLAS's Electron Beam Ion Sources

The basic operating principle of the EBIS system is to trap ions within the electron beam and breed them. An electron beam is produced by the electron gun, accelerated by the drift tubes, and then compressed by the superconducting solenoid magnetic field. Upon leaving the solenoid the beam is then dumped into an electron collector. Ions from the CARIBU source are injected into the EBIS system and confined within the same space as the electron beam. The ions are trapped transversely due to the solenoid's large central field and the space charge of the electron beam, and are trapped longitudinally through an externally applied potential to the end drift tubes. Once trapped, the ions become highly charged through electron collisions before they are extracted for use in the accelerator.

In the EBIS system having a stable and well defined electron beam is very important to insure that the system preforms properly and is not damaged. The electron beam is DC, losses of the electron

beam on components other than the collector can cause significant damage. The beam stability was studied with two different facets; external magnetic field uniformity and understanding the effect of drift tube misalignments. These were studied using Computer Simulation Technology's (CST) electromagnetic solver and particle tracking solver. CST is a three dimensional numerical modeler and solver used to solve for electro and magneto static fields and tracks electrons.

Parameter	High Current E-Gun
Superconducting Solenoid Central Field	6.0 Tesla
Magnetic Field at Cathode	0.15 Tesla
Diameter of IrCe Thermionic Cathode	42 mm
Electron Beam Energy in the Trap	6693 eV
Maximum Operational Axial Magnetic Field of Turbo Pumps	150 G
Maximum Operational Radial Magnetic Field of Turbo Pumps	30 G

## 2. Turbo Pump Modeling

### 2.1 Determining the Force Exerted on the Turbo Pumps and Shields

Ions may be confined within the trap for up to 1 second to optimize the breeding efficiencies and achieve the necessary charge-to-mass ratio. If the vacuum is not high enough in the trap then ionized background gas can become non-negligible in the beam. Facilities such as Brookhaven National Lab's T-EBIS and REXEBIS have shown that vacuum pressures in the trap of  $10^{-11} - 10^{-12}$  Torr [2] are sufficient to keep the beam pure for this type of system. At ATLAS, this is achieved by three turbo pumps placed around the system. The approximate locations of the turbo pumps are illustrated in Fig 2.

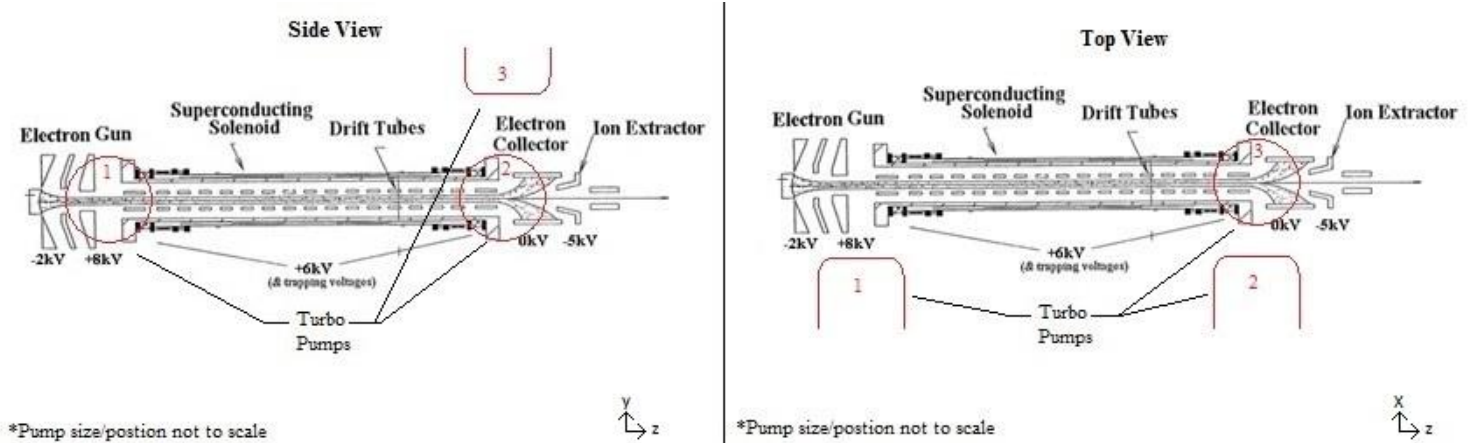


Figure 2: Turbo pump positions

The turbo pumps have a maximum magnetic field that they can operate in of 150 G axially and 30 G radially. However, the fringe magnetic field at the location of the turbo pump locations is much larger than

this. Rather than moving the turbo pumps further away and lowering pumping speeds and efficiencies, the pumps have been shielded. Since these shields interact strongly with the magnetic field, there is a non-negligible force that is exerted on the shields. Using Computer Simulation Technology's (CST) particle studio, the configuration was modeled. The forces and torques were found using the solver's force calculator (Table 1).

<b>Torques</b>	X - Component	Y - Component	Z - Component	
Shield 1	1.0364 Nm	84.709 Nm	1.4578 Nm	
Shield 2	-0.43136 Nm	-75.880 Nm	0.56869 Nm	
Shield 3	46.329 Nm	-0.67322 Nm	-3.5218 Nm	
<b>Forces</b>	X - Component	Y - Component	Z - Component	Magnitude
Shield 1	168.31 N	-1.3411 N	-42.562 N	173.61 N
Shield 2	145.97 N	-0.48883 N	47.272 N	153.44 N
Shield 3	0.57328 N	-113.66 N	-110.7 N	158.66N

Table 1: Force calculations on the turbo pump shields

With the forces, proper precautions to mount the shields are being taken.

## 2.2 Determining the On-axis Magnetic Field Deviations Caused by the Shields

As discussed in section 2.1, the turbo pumps are shielded in order to interfere with the magnetic field to limit the field in which the turbo pump motors operate. Unfortunately, the magnetic field from the solenoid induces a magnetic field in the shields which interacts with the electron beam. The electrons are light and at relatively low energies, so even small changes in the magnetic field can cause noticeable deviations in the electron beam. The magnetic field from the shields on beam axis was identified using CST's magneto static solver (Figure 3).

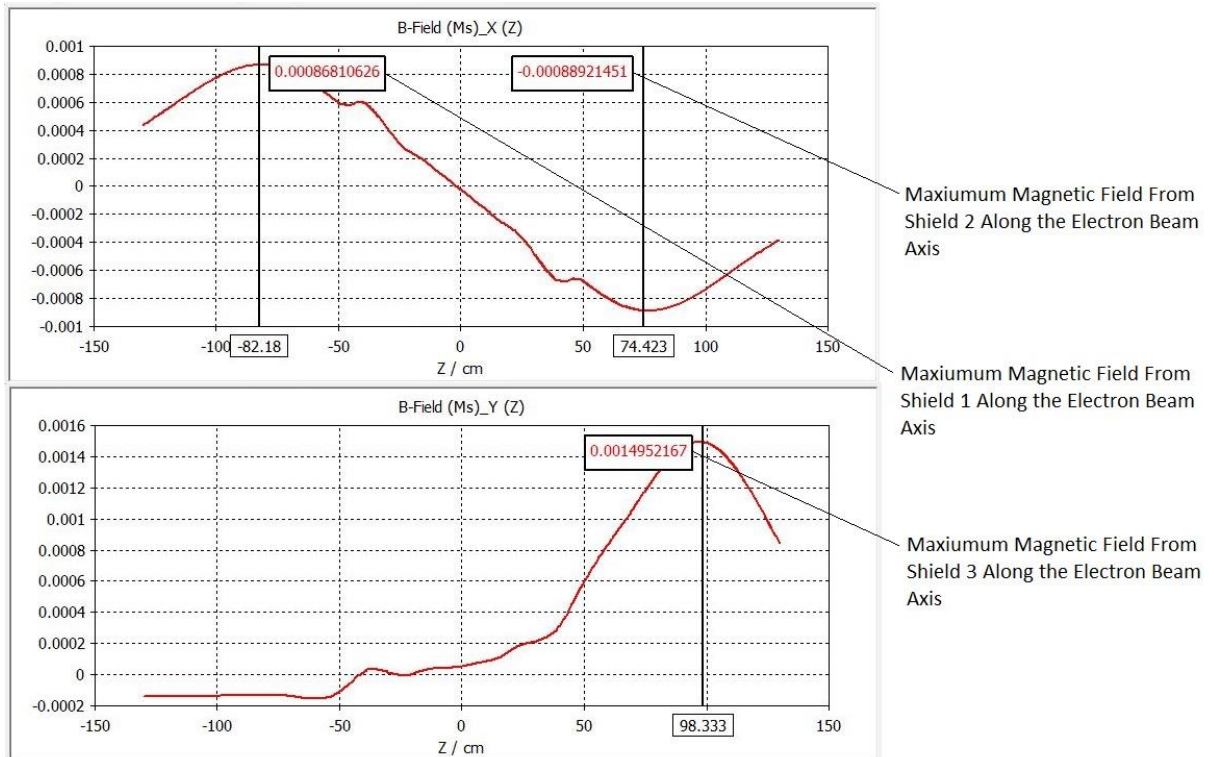


Figure 3: Magnetic field from turbo pump shields

These graphs show the x-component and y-components of the magnetic field on axis. The magnetic field from an ideal solenoid is purely in the z-direction on axis. After verifying that this was the case of this solenoid, it was concluded that the x-component and y-component are purely the result of the shields. Using Computer Simulation Technology's EM Studio, it was found that the maximum fields on the beam axis from shields 1, 2 and 3 are 8.7 Gauss, -8.9 Gauss, and 15.0 Gauss respectively. There is no net deviation cause by the first and second shields (x-direction).

## 2.3 Minimizing the Beam Deviation Due to the Shield's B-Field

In section 2.2, the magnetic fields from the turbo pump shields were found. The currently proposed solution is to design Helmholtz coils to counteract this deviation. For an ideal Helmholtz coil which results in the maximum field uniformity, the magnetomotive force (MMF), the number of turns(n) times the current (I), for the Helmholtz coils is given by:

$$nI = B_o \left( \frac{R}{\mu_o} \right) \left( \frac{5}{4} \right)^{3/2}$$

Where  $B_o$  is the magnetic field at the geometric center of the coils,  $R$  is the radius of the infinitely thin wire loops, and  $\mu_o$  is the permeability of free space. Two ideal designs were tested in CST EM suites. These designs had radii of 8.1 inches and 10.1 inches. Using the maximum field values found in part 2.2 for  $B_o$ , the number of turns\*current given by this equation matched the results produced by CST's EM suite to within three percent. After verifying the model's validity, the design was changed for practicality. Two non-ideal designs were proposed and modeled (Figure 4).

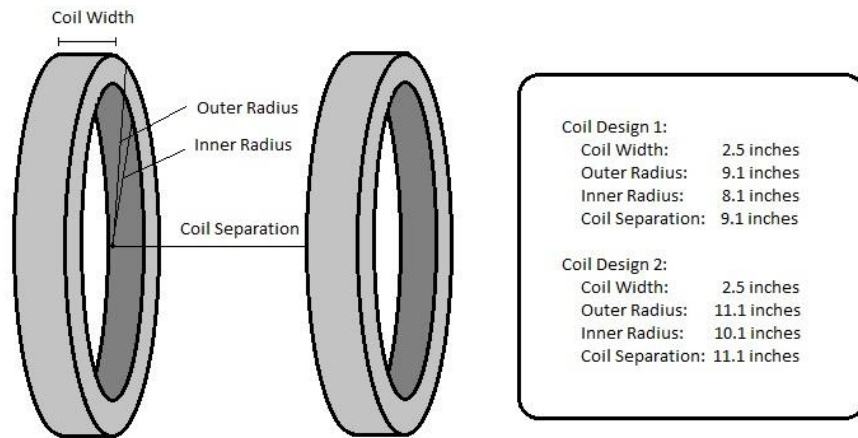


Figure 4: Non-ideal Helmholtz coil design

Using these designs, the MMF was found such that the maximum field at the geometric center of the coils matches the maximum field due to each shield on the beam axis. These results are shown in Table 2. In addition to this, the fields were exported and the MMF for the integrals of the two fields over the regions just outside the solenoid to be equal and opposite were calculated for both proposed design. These results are shown in table 2. Using the 'complete match' number, the total deviation that the particles in the beam see over this region should be zero and the effects of the shields on the beam completely nullified.

Max Field Match	Shield 1	Shield 2	Shield 3
8.1" Inner Radius	332 A*Turns	340 A*Turns	572 A*Turns
10.1" Inner Radius	380 A*Turns	389 A*Turns	655 A*Turns
Complete Match	Shield 1	Shield 2	Shield 3
8.1" Inner Radius	235 A*Turns	241 A*Turns	405 A*Turns
10.1" Inner Radius	269 A*Turns	275 A*Turns	464 A*Turns

Table 2: The MMF necessary to nullify the shield's effect on beam axis

### 3. Drift Tube Modeling

#### 3.1 Drift Tube Model Design Specifications

##### 3.1.1 Particle Beam

The EBIS is designed to be able to utilize two thermionic electron guns, e-guns; a high-current, 2 A, and a low-current, 0.2 A, e-gun. For the purpose of these simulations, the design specifications of the 2 A IrCe gun were used. This gun was designed with a radius,  $r_{gun}$ , of 42mm. The radius of the beam at any point in the system is then given by:

$$r_{beam} = r_{gun} \sqrt{\frac{B_{gun}}{B_{beam}}}$$

Where  $r_{beam}$  is the radius of the beam at any point along the trap,  $B_{gun}$  is the magnetic field at the gun, and  $B_{beam}$  is the magnetic field at the point in the trap where  $r_{beam}$  is calculated. The nominal magnetic field at the gun is 0.15 T so within the 6 T superconducting solenoid, the beam radius is 316  $\mu\text{m}$ . The energy of the beam in the center of the superconducting solenoid is 6693 eV.

The cathodes of both e-guns were rounded and a shield was added around the cathode in order to create a beam with approximately uniform distribution. 124 uniformly distributed particles were used to simulate the beam in CST Particle Suite. For this model, the beam was simulated to start directly in the center of a drift tube with all the parameters discussed above. However, since there is no beam behind the artificially injected beam, space charge was strong enough to keep large amounts of the beam from ever leaving the injection site. CST did not allow for the creation of the necessary symmetry or boundary conditions to solve this problem. So, in order to counteract this particles, two particles were launched from the same location with the same parameters but in opposite directions. This created the missing mirrored electric field caused by the space charge.

This beam will be an idealized case, the injected beam has no angular component upon injection as well as perfectly uniform distribution. Due to numerical inaccuracies, the energy of the beam is 6729 eV rather than 6693 eV. There is no spread in the kinetic energy. Additionally, the 124 simulated particles has a much smaller current density than the 2.0 A e-gun. That being said this idealized and simplified beam yields representative results of how the beam will act within the trap.

##### 3.1.2 Magnetic Field

For this model the magnetic field used is entirely produced by the 6 T superconducting solenoid around the trap region. In the actual system, this field is a superposition of the fields from the three shields, the solenoids around the trap, the electron gun and the ion extractor. However, all of the fields except for

the solenoid around the trap contribute minimally to the total field in this region. For this reason, they have been excluded from the model. It should be noted however, that the central field is entirely in the z-direction. Some of these other fields may add noticeable fields in the x-direction and the y-direction. However, these fields are still negligible by comparison to the total magnetic field strength in this region.

The superconducting solenoid has a nominal magnetic field on the electron beam axis of 6 T within the trap region.

### 3.2 Preliminary Results on the Effect of Drift Tube Misalignments on the Beam Emittance

Preliminary results have been found for how the emittance changes as a function of the offset angle between two drift tubes. These results were found using the particle tracker's position monitor. A representative envelope of the emittance of the electron beam as it passes through the first drift tube, accelerating region between the two tubes and then passes through the second drift tube is shown below (Figure 5). This specific example is between two drift tubes with no angular offset and a potential on the first tube of 6,000 Volts and a potential on the second drift tube of 4,000 Volts.

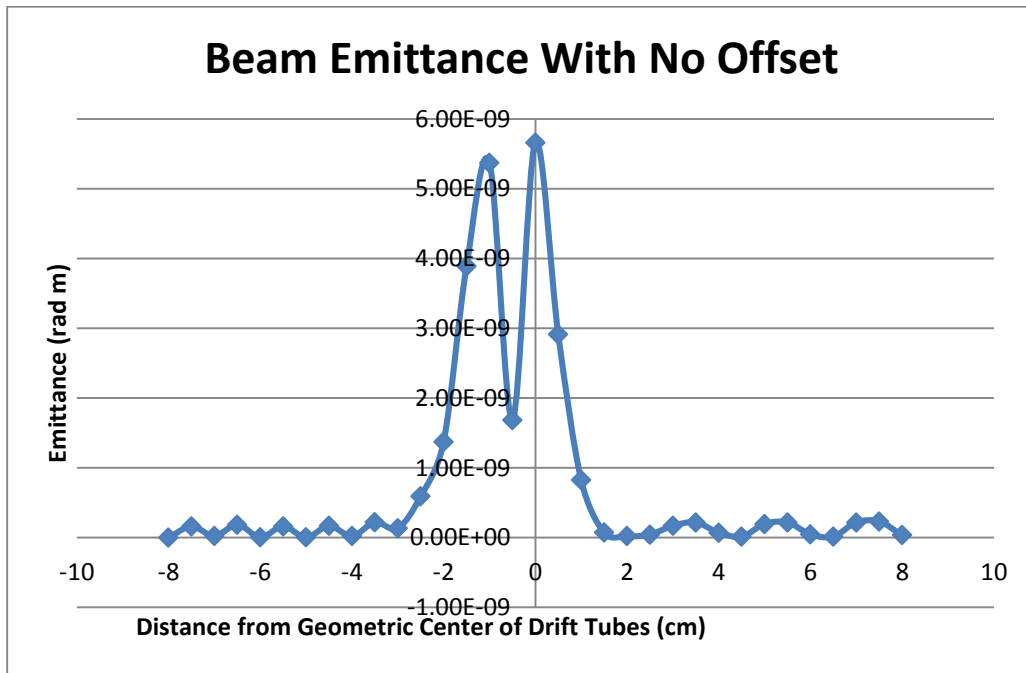


Figure 5: Representative beam envelope

This envelope is highly representative of the envelopes when there is no angular offset. One specific quality that should be highlighted in this envelope is the oscillating emittances in the stable drift tube regions. These oscillations could be due to non-linear focusing forces or artifacts of the simulation, but the specific cause has yet to be identified. The percent difference in the average emittance inside the stable regions of both of drift tube one and drift tubes (3 cm – 8cm) as a function of angular off set has also been studied (Figure 6).

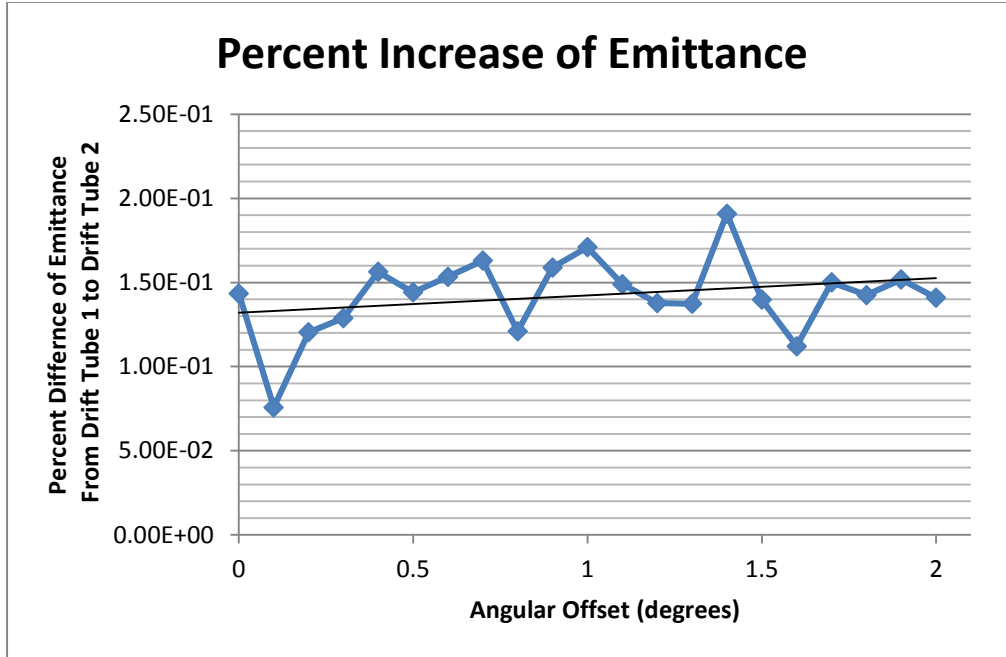


Figure 6: Percent difference between the average emittance in drift tube 1 and drift tube 2

There are two primary features that should be highlighted from Figure 6. There is an offset of 1.03 percent which is likely the cause of the emittances being non-normalized. In addition to the offset there is a linear offset. Although this linear offset seems to point to an increase in the average emittance with angle, there are too many numerical inaccuracies to draw any definitive conclusions on the effect of a change in angle on emittance. Although not complete, these preliminary results are a major stepping stone in improving and completing the model as well as determining the final project results.

## 4. Conclusion and Future Work

In this study the forces on ATLAS's EBIS turbo pumps from the system's magnets were identified. Additionally shields for these pumps were modeled and the effect of these shields on the electron beam were determined. Helmholtz coils were designed to counteract the effect of these shields. A model to analyze the effects of drift tube misalignments was also constructed and preliminary results on how angular misalignments change beam emittance were determined.

Future work includes verifying the drift tube misalignments measurements as well as expanding the scope of these measurements to take into account factors such as different drift tube voltages, different drift tube positioning within the trap and various other parameters. These parameters should be specifically tailored to the set-up currently implemented in the EBIS system. In addition to this work, the magnetic field measurements should be continued by implementing the Helmholtz coil designs as well as taking into account the forces on the turbo pump mounts.

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